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The IIA super-eightbrane

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ABSTRACT

We present a version of ten-dimensional IIA supergravity containing a 9-form potential for which the field equations are equivalent to those of the standard, massless, IIA theory for vanishing 10-form field strength, F_{10} , and to those of the ‘massive’ IIA theory for non-vanishing F_{10} . We exhibit a multi 8-brane solution of this theory which preserves half the supersymmetry. We propose this solution as the effective field theory realization of the Dirichlet 8-brane of type IIA superstring theory.

1. Introduction

Recent advances in our understanding of non-perturbative superstring theory have led to the establishment of many connections between hitherto unrelated superstring theories. Many of these connections involve p-brane solutions of the respective supergravity theories that couple to the (p+1)-form potentials in the Ramond-Ramond (RR) sector. These RR p-branes are all singular as solutions of ten-dimensional (D=10) supergravity, so their status in superstring theory was unclear until recently. It now appears that the RR p-branes of type II supergravity theories have their place in type II superstring theory as ‘Dirichlet-branes’, or ‘D-branes’ [1]. These include the p-branes for $p = 0, 2, 4, 6$ in the type IIA case and the p-branes for $p = 1, 3, 5$ in the type IIB case. However, they also include a type IIB (-1)-brane (instanton) and a 7-brane [2], and a type IIA 8-brane.

Since p-branes couple naturally to (p+1)-form potentials, the existence of an 8-brane in type IIA D=10 superstring theory suggests the existence of a corresponding 9-form potential, A_9 , with 10-form field strength, F_{10} , in the effective type IIA supergravity theory. Assuming a standard kinetic term of the form F_{10}^2 , the inclusion of this field does not lead to any additional degrees of freedom (per spacetime point) and so is not immediately ruled out by supersymmetry considerations, but it allows the introduction of a cosmological constant [1], as explained many years ago in the context of a four-form field strength in four-dimensional field theories [3, 4]. As it happens, a version of type IIA supergravity theory with a cosmological constant was constructed some time ago by Romans [5], who called it the ‘massive’ IIA supergravity theory. This theory has the peculiarity that D=10 Minkowski spacetime is *not* a solution of the field equations (and neither is the product of D=4 Minkowski spacetime with a Calabi-Yau space). Various Kaluza-Klein (KK) type solutions were found by Romans but none of them were supersymmetric, i.e. these solutions break all the supersymmetries.

Here we shall present the 10-form reformulation of Romans’ theory. The new IIA supergravity theory has the advantage that its solutions include those of both

the massless and the massive IIA theory. We propose this new IIA supergravity theory as the effective field theory of the type IIA superstring, allowing for the 9-form potential. It has been suggested [1,6] that the expectation value of the dual of the 10-form field strength of this superstring theory should be interpreted as the cosmological constant of the massive IIA supergravity theory. One result of this paper is the determination of the precise relation between these quantities; they are conjugate variables in a sense discussed previously in the D=4 context [7]. Our main result is the construction of multi 8-brane solutions of the new IIA supergravity theory which preserve half the supersymmetry. These solutions are singular at the ‘centres’ of the metric, but this is a general feature of RR p-branes. We propose these solutions as the effective field theory realization of Dirichlet 8-branes of type IIA superstring theory.

We begin with a review of the massive IIA supergravity, introducing some simplifications. We then construct the new formulation of the bosonic sector of this theory, incorporating the 9-form gauge field A_9 , in which the cosmological constant m emerges as an integration constant. We then construct a supersymmetric 8-brane solution of the massive IIA supergravity theory and show that it has a generalization to multi 8-brane solutions of the new IIA theory. The latter solutions include some which are asymptotically flat. We shall comment further on the relation to type IIA superstring theory in the conclusions.

2. The massive IIA supergravity

The bosonic field content of the massive IIA D=10 supergravity theory comprises (in our notation) the (Einstein) metric, $g^{(E)}$, the dilaton, σ , a massive 2-form tensor field B' and a three-form potential C' . One introduces the field-strengths

$$\begin{aligned} G &= 4dC' + 6m(B')^2 \\ H &= 3dB' \end{aligned} \tag{2.1}$$

where m is a mass parameter. The Lagrangian for these fields is [5]

$$\begin{aligned} \mathcal{L} = & \sqrt{-g^{(E)}} \left[R_{(E)} - \frac{1}{2} |\partial\sigma|^2 - \frac{1}{3} e^{-\sigma} |H|^2 - \frac{1}{12} e^{\frac{1}{2}\sigma} |G|^2 - m^2 e^{\frac{3}{2}\sigma} |B'|^2 - \frac{1}{2} m^2 e^{\frac{5}{2}\sigma} \right] \\ & + \frac{1}{9} \varepsilon [dC' dC' B' + m dC' (B')^3 + \frac{9}{20} m^2 (B')^5] . \end{aligned} \quad (2.2)$$

The notation for forms being used here is that a q -form Q has components $Q_{M_1 \dots M_q}$ given by

$$Q = Q_{M_1 \dots M_q} dx^{M_1} \wedge \dots \wedge dx^{M_q} . \quad (2.3)$$

Thus, the $(1/9)\varepsilon dC' dC' B'$ term in (2.2) is shorthand for

$$\frac{1}{9} \varepsilon^{M_1 \dots M_{10}} \partial_{M_1} C'_{M_2 M_3 M_4} \partial_{M_5} C'_{M_6 M_7 M_8} B_{M_9 M_{10}} . \quad (2.4)$$

As explained in [5] the massless limit is not found by simply setting $m = 0$ in (2.2) because the supersymmetry transformations involve terms containing m^{-1} . Instead, one first makes the field redefinitions

$$\begin{aligned} B' &= B + \frac{2}{m} dA \\ C' &= \tilde{C} - \frac{6}{m} A dA . \end{aligned} \quad (2.5)$$

This redefinition introduces the gauge invariance

$$\begin{aligned} \delta A &= -m\Lambda \\ \delta B &= 2d\Lambda \\ \delta \tilde{C} &= 12A d\Lambda \end{aligned} \quad (2.6)$$

for which the gauge-invariant field strengths are

$$\begin{aligned} F &= 2dA + mB \\ H &= 3dB \\ G &= 4d\tilde{C} + 24BdA + 6mB^2 . \end{aligned} \quad (2.7)$$

The bosonic Lagrangian of the massive IIA theory is now

$$\begin{aligned} \mathcal{L} = & \sqrt{-g^{(E)}} \left[R_{(E)} - \frac{1}{2}|\partial\sigma|^2 - \frac{1}{3}e^{-\sigma}|H|^2 - \frac{1}{12}e^{\frac{1}{2}\sigma}|G|^2 - e^{\frac{3}{2}\sigma}|F|^2 - \frac{1}{2}m^2e^{\frac{5}{2}\sigma} \right] \\ & + \frac{1}{9}\varepsilon [d\tilde{C}d\tilde{C}B + 6d\tilde{C}B^2dA + 12(dA)^2B^3 + md\tilde{C}B^3 + \frac{9}{2}mB^4dA + \frac{9}{20}m^2(B)^5] , \end{aligned} \quad (2.8)$$

and the bosonic Lagrangian of the massless IIA theory can now be found by taking the $m \rightarrow 0$ limit.

The Lagrangian (2.8) can be simplified by the further redefinition

$$\tilde{C} = C - 6AB . \quad (2.9)$$

The Λ -gauge transformation of the new 3-form C is

$$\delta C = -6m\Lambda B \quad (2.10)$$

and the gauge-invariant field strengths, F , H , and G are now given by

$$\begin{aligned} F &= 2dA + mB \\ H &= 3dB \\ G &= 4dC + 24AdB + 6mB^2 . \end{aligned} \quad (2.11)$$

At the same time, to make contact with string theory, it is convenient to introduce the string metric

$$g_{MN} = e^{-\frac{1}{2}\sigma} g_{MN}^{(E)} . \quad (2.12)$$

The bosonic Lagrangian now takes the simple form

$$\begin{aligned} \mathcal{L} = & \sqrt{-g} \{ e^{-2\sigma} [R - \frac{1}{2}|\partial\sigma|^2 - \frac{1}{3}|H|^2] - |F|^2 - \frac{1}{12}|G|^2 - \frac{1}{2}m^2 \} \\ & + \frac{1}{9}\varepsilon [dCdCB + m dCB^3 + \frac{9}{20}m^2(B)^5] . \end{aligned} \quad (2.13)$$

Observe that the final topological term is simply a type of Chern-Simons (CS) term associated with the 11-form G^2H . Thus, the bosonic action of the massive

type IIA supergravity theory can be written as

$$\begin{aligned}
I = \int_{\mathcal{M}_{10}} d^{10}x \sqrt{-g} \Big\{ e^{-2\sigma} \left[R - \frac{1}{2} |\partial\sigma|^2 - \frac{1}{3} |H|^2 \right] - |F|^2 - \frac{1}{12} |G|^2 - \frac{1}{2} m^2 \Big\} \\
+ \frac{1}{9} \int_{\mathcal{M}_{11}} G^2 H \ ,
\end{aligned} \tag{2.14}$$

where \mathcal{M}_{11} is an 11-manifold with boundary \mathcal{M}_{10} . Apart from the cosmological constant, the m -dependent terms in the action can be simply understood as arising from the replacement of the usual m -independent field strengths of the massless type IIA theory by their m -dependent generalizations (2.11). Furthermore, the m -dependence of these field strengths is completely fixed by the ‘shift’ gauge transformation $\delta A = -m\Lambda$ of A , as are the Λ -gauge transformations. The relation of the constant m appearing in this transformation with the cosmological constant cannot be understood purely within the context of the bosonic Lagrangian but is, of course, fixed by supersymmetry.

Observe that the cosmological constant term in (2.14) is now (in the string metric) independent of the dilaton. This is typical of the RR sector and is consistent with the idea that m can be interpreted as the expectation value of the dual of a RR 10-form field strength. This interpretation would have the additional virtue of restoring the invariance under the discrete symmetry in which all RR fields change sign, a symmetry that is broken by the terms linear in m in (2.13). We shall now show how to reformulate the massive IIA theory along these lines. As we shall see the cosmological constant is simply related to, but not equal to, the expectation value of the ten-form field strength.

3. IIA supergravity with 9-form potential

We shall start with the bosonic Lagrangian of (2.13). Expanding in powers of m , the associated action $I(m)$ is

$$I(m) = I(0) + \int d^{10}x \left\{ 2m\sqrt{-g}[(dC + 6AdB) \cdot B^2 - 2dA \cdot B] + \frac{m}{9}\varepsilon dCB^3 \right. \\ \left. - \frac{1}{2}m^2\sqrt{-g}[1 + 2|B|^2 + 6|B^2|^2] + \frac{m^2}{20}\varepsilon B^5 \right\} , \quad (3.1)$$

where $I(0)$ is the bosonic action of the massless IIA supergravity theory. We now promote the constant m to a field $M(x)$, at the same time introducing a 9-form potential A_9 as a Lagrange multiplier for the constraint $dM = 0$. Omitting a surface term, the Lagrange multiplier term can be rewritten as

$$10 \varepsilon dA_9 M . \quad (3.2)$$

The A_9 field equation implies that $M = m$, for some constant m , so the the remaining equations are equivalent to those of the massive IIA theory except that the constant m is now arbitrary and that we now have an additional field equation from varying M . This additional equation is

$$\frac{\delta I(M)}{\delta M(x)} = -\varepsilon F_{10} \quad (3.3)$$

where $I(M)$ is the action (3.1) but with M replacing m , and $F_{10} = 10 dA_9$ is the 10-form field strength of A_9 . Thus the M equation simply determines the new field strength F_{10} . Observe that the expectation value of (εF_{10}) is *not* equal to the expectation value of $\sqrt{-g}M$, as a matter of principle (although it may equal it in special backgrounds) , but is rather the value of the variable canonically conjugate to it.

Note that the gauge and supersymmetry transformations of the action $I(M)$ no longer vanish. However, the variations of $I(M)$ are proportional to dM and can

therefore be cancelled by a variation of the new 9-form gauge potential A_9 . This determines the gauge and supersymmetry transformations of A_9 . The supersymmetry variation will not be needed for our purposes so we omit it. The Λ -gauge transformation of A_9 found in this way is

$$\delta(\varepsilon A_9) = \frac{2}{5}\sqrt{-g}\left[\Lambda \cdot F + (\Lambda B) \cdot G\right] - \frac{1}{30}\varepsilon(2\Lambda dC B^2 + M\Lambda B^4) . \quad (3.4)$$

We now have a new gauge-invariant bosonic action

$$I(M) + \int d^{10}x \, M \varepsilon F_{10} . \quad (3.5)$$

The field M can now be treated as an auxiliary field that can be eliminated via its field equation

$$\sqrt{-g}M = K^{-1}(B)\left\{\varepsilon(F_{10} + \frac{1}{9}dC B^3) + 2\sqrt{-g}[(dC + 6AdB) \cdot B^2 - 2dA \cdot B]\right\} , \quad (3.6)$$

where

$$K(B) = 1 + 2|B^2| + 6|B^2|^2 - \frac{1}{10\sqrt{-g}}\varepsilon B^5 . \quad (3.7)$$

Using this relation in (3.5) we arrive at the Lagrangian

$$\mathcal{L}_{new} = \mathcal{L}_0 + [\sqrt{-g}K(B)]^{-1}\left\{\varepsilon(F_{10} + \frac{1}{9}dC B^3) + 2\sqrt{-g}[(dC + 6AdB) \cdot B^2 - 2dA \cdot B]\right\}^2 \quad (3.8)$$

where \mathcal{L}_0 is the bosonic Lagrangian of the massless IIA theory. Note the non-polynomial structure of the new Lagrangian in the gauge field B . This greatly obscures the Λ -gauge invariance, which is ensured by the very complicated Λ -gauge transformation of A_9 .

4. The Eightbrane

The appearance of the 9-form potential in the above reformulation of the massive IIA supergravity theory suggests the existence of an associated 8-brane solution. We will find solutions of the equations of motion of (3.8) of the form

$$\begin{aligned} ds_{(E)}^2 &= f^2(y) dx^\mu dx^\nu \eta_{\mu\nu} + dy^2 \\ \sigma &= \sigma(y) \\ A_9 &= A_9(y) \end{aligned} \tag{4.1}$$

with all other fields vanishing, and where η is the Minkowski 9-metric. Such a solution will have 9-dimensional Poincaré invariance and hence an interpretation as an 8-brane. We shall further require of such a solution that it preserve some supersymmetry, so we shall begin by considering the variation of the gravitino one-form ψ and the dilatino λ in the presence of configurations of the above form. The full variations of the massive IIA theory can be found in [5]. They depend on the constant m . In the new theory, this constant is replaced by the function M given in (3.6). For the backgrounds considered here, $\sqrt{-g}M = \varepsilon F_{10}$ and the supersymmetry variations of the fermions reduce to

$$\begin{aligned} \delta_\epsilon \psi &= D\epsilon - \frac{1}{32} M e^{\frac{5}{4}\sigma} \Gamma \epsilon \\ \delta_\epsilon \lambda &= -\frac{1}{2\sqrt{2}} \left(\Gamma^M \partial_M \sigma + \frac{5}{4} M e^{\frac{5}{4}\sigma} \right) \epsilon . \end{aligned} \tag{4.2}$$

For configurations of the assumed form and further assuming that ϵ depends only on y , the equations $\delta\psi = 0$ and $\delta\lambda = 0$ become

$$\begin{aligned} 0 &= \epsilon' - \frac{1}{32} M e^{\frac{5}{4}\sigma} \Gamma_y \epsilon \\ 0 &= \left(f' \Gamma_y - \frac{1}{16} M f e^{\frac{5}{4}\sigma} \right) \epsilon \\ 0 &= \left(\sigma' + \frac{5}{4} M e^{\frac{5}{4}\sigma} \Gamma_y \right) \epsilon , \end{aligned} \tag{4.3}$$

where the prime indicates differentiation with respect to y . To find non-zero solu-

tions for ϵ we are now forced to suppose that

$$\Gamma_y \epsilon = \pm \epsilon . \quad (4.4)$$

We then find that

$$f' = \pm \frac{1}{16} M f e^{\frac{5}{4}\sigma} \quad (4.5)$$

and that

$$\left(e^{-\frac{5}{4}\sigma} \right)' = \pm \frac{25}{16} M . \quad (4.6)$$

Eliminating M from these equations we deduce that

$$f = A e^{-\frac{1}{20}\sigma} , \quad (4.7)$$

for some constant A . Using now the A_9 field equation $M' = 0$, (4.6) is seen to imply that

$$\partial_y^2 \left(e^{-\frac{5}{4}\sigma} \right) = 0 . \quad (4.8)$$

The general solution is given in terms of a harmonic function $V(y)$, the precise nature of which will be discussed shortly, i.e.

$$e^{-\frac{5}{4}\sigma} = V(y) . \quad (4.9)$$

Equation (4.6), together with (4.7), now gives

$$M = \mp \frac{16}{25} V' , \quad f = A V^{\frac{1}{25}} . \quad (4.10)$$

In principle, we have still to consider the other field equations, but we have checked that they are all solved by the above field configurations. The Einstein metric of

the multi 8-brane solution is

$$ds_{(E)}^2 = A^2 V^{\frac{2}{25}}(y) dx^\mu dx^\nu \eta_{\mu\nu} + dy^2 . \quad (4.11)$$

The string metric is

$$ds^2 = A^2 V^{\frac{12}{25}} dx^\mu dx^\nu \eta_{\mu\nu} + V^{\frac{2}{5}} dy^2 . \quad (4.12)$$

The Killing spinor ϵ is given by

$$\epsilon = V^{\frac{1}{50}} \epsilon_0, \quad \Gamma_y \epsilon_0 = \pm \epsilon_0 , \quad (4.13)$$

where ϵ_0 is a constant spinor.

It remains to determine the function V . Consider first the massive IIA theory for which the function M equals the (non-zero) constant m appearing in the Lagrangian, which we may choose to be positive. In this case

$$V = \pm \frac{25}{16} m (y - y_0) \quad (4.14)$$

where the sign depends on the choice of chirality of ϵ . However, V must be positive for real σ , so the spinor ϵ must change chirality at $y = y_0$. This is possible because the spinor ϵ vanishes at $y = y_0$. This is acceptable because the metric (either the Einstein or the string one) is also singular at $y = y_0$. Thus, the massive IIA theory has a solution for which

$$V = \frac{25}{16} m |y - y_0| . \quad (4.15)$$

Note that V is a continuous function of y with a kink singularity at $y = y_0$, at which the curvature tensor has a delta function singularity.

In the new IIA theory we may suppose that M is only *locally* constant. The form of the function $V(y)$ in this case depends on the type of point singularity that

we allow. The above example suggests that we should require V to be a continuous function of y . There are solutions with discontinuities in V but they have δ' type singularities of the curvature tensor, and we shall not consider them. In any case, the restriction to kink singularities produces physically sensible results, as we shall see. An example of a solution with a single kink singularity of V is

$$V = \begin{cases} -ay + b & y < 0 \\ cy + b & y > 0 \end{cases} \quad (4.16)$$

where a , b and c are non-negative constants. We adopt this as the basic single 8-brane solution. It can be interpreted as a domain wall separating regions with different values of M . The solution has two asymptotic regions relative to which an 8-brane charge, Q_{\pm} , may be defined as the value of M as $y \rightarrow \pm\infty$. For the above solution,

$$Q_+ = c \quad Q_- = a \quad (4.17)$$

The multi 8-brane generalization of (4.16) with the same charges is found by allowing kink singularities of V at $n+1$ ordered points $y = y_0 < y_1 < y_2 < \dots < y_n$. The function V is

$$V = \begin{cases} -a(y - y_0) + \sum_{i=1}^n \mu_i (y_i - y_0) + b & y < y_0 \\ (c - \sum_{i=1}^n \mu_i) |y - y_0| + \sum_{i=1}^n \mu_i |y - y_i| + b & y > y_0 \end{cases} \quad (4.18)$$

where μ_i are positive constants and a , b , c are non-negative constants.

The asymptotically left-flat or right-flat solutions are those for which $Q_- = 0$ or $Q_+ = 0$, respectively. The asymptotically flat solutions are those which are both asymptotically left-flat and right-flat. An example of an asymptotically flat three 8-brane solution is given by $V = \mu^2 ||y - y_0| - |y - y_1|| + \gamma^2$, where μ and γ are arbitrary constants.

5. Comments

One obvious point to be considered is the nature of the nine-dimensional world-volume field theory governing the dynamics of small perturbations about the static single 8-brane solution. Since the solution preserves half the D=10 type II supersymmetry, this worldvolume field theory must have N=1 six-dimensional supersymmetry. It must also include one Nambu-Goldstone scalar field corresponding to the breaking of translational invariance in the y direction. Given that the worldvolume action does not include fields of spin greater than one, there is a unique candidate that fulfils these requirements, namely the nine-dimensional super-Maxwell multiplet. This result is suggestive. Note that the 8-brane solution (4.11) can be double-dimensionally reduced to yield a membrane in a D=4 N=8 theory (by periodic identification of six spatial coordinates). Given that the worldvolume fields of the membrane are those of a nine-dimensional super-Maxwell multiplet, the worldvolume fields of the D=4 membrane will be those of an N=8 three-dimensional super-Maxwell multiplet, which is equivalent by dualization of the vector field to the worldvolume supermultiplet of the D=11 supermembrane. This suggests a possible connection of the massive IIA supergravity to D=11 supergravity via the reduction of the D=11 supermembrane to D=4. As a solution of D=11 supergravity, the latter is also determined in terms of a single harmonic function V . Normally V is harmonic on the transverse eight-dimensional Euclidean space, but after compactification on T^7 to D=4 we need a harmonic function on $\mathbb{R} \times T^7$. The solution that is constant on T^7 is therefore similar to that given above for the type II 8-brane and we have verified that it is a supersymmetric solution of the massive N=8 D=4 supergravity theory constructed in [4], so its status is rather similar to that of the 8-brane solution of the massive type IIA supergravity.

The single 8-brane solution described in this paper should be related to the Dirichlet 8-brane of [1]. This is a string background in which open string states arise with fixed (Dirichlet) boundary conditions that are imposed in one space-like dimension at one or both ends of the string. These conditions restrict at least one

of the end-points of open strings to lie in the nine-dimensional worldvolume of an 8-brane. The 8-brane couples to a 9-form gauge field with a ten-form field strength F_{10} . If the new IIA supergravity constructed here is indeed the effective field theory of the IIA superstring in the presence of this 10-form field strength then it should be possible to recover the Lagrangian (3.8) by string theory considerations. Neglecting terms of order B^2 , which in any case follow from gauge invariance, the only term in (3.8) that is linear in F_{10} is proportional to

$$(\varepsilon F_{10}) dA \cdot B . \quad (5.1)$$

This is the crucial term that has to be reproduced in string theory. There is a vertex operator in the RR sector of the type IIA theory that couples a ten-form field strength to the worldsheet. This vertex operator has the form $F_{10} \bar{S} S$, where S is the spacetime spinor worldsheet field of the spacetime supersymmetric worldsheet action. There are non-trivial tree diagrams that mix F_{10} with fields from the RR and NSNS sectors, producing a term of the form (5.1), as required. The requirements of gauge invariance suggest that a more systematic consideration of string theory in the presence of D-branes would produce the full effective Lagrangian (3.8).

Since all the p -brane solutions of D=10 IIA supergravity for $p < 8$ can be viewed as arising from some 11-dimensional ‘M-theory’ [8,9,10,11], it would be surprising if the 8-brane did not also have an 11-dimensional interpretation. The obvious possibility is that the D=10 8-brane is the double-dimensional reduction of a D=11 supersymmetric 9-brane. Such an object would be expected (see [12]) to carry a 9-form ‘charge’ appearing in the D=11 supertranslation algebra as a central charge. This is possible because the 2-form charge normally associated with the D=11 supermembrane is algebraically equivalent to a 9-form. It is not easy to see how to implement this idea, however, since there is no ‘massive’ D=11 supergravity theory. One possibility is suggested by the recent interpretation [11] of the heterotic string as an S^1/\mathbb{Z}_2 compactified M-theory. Since the compactification

breaks half the supersymmetry and the compactifying space is actually the closed interval, the two D=10 spacetime boundaries might be viewed as the worldvolumes of two D=11 9-branes.

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